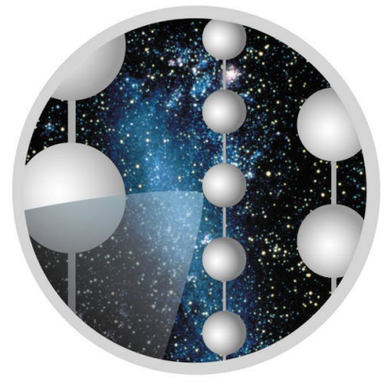
Neutrino Oscillations with IceCube/PINGU

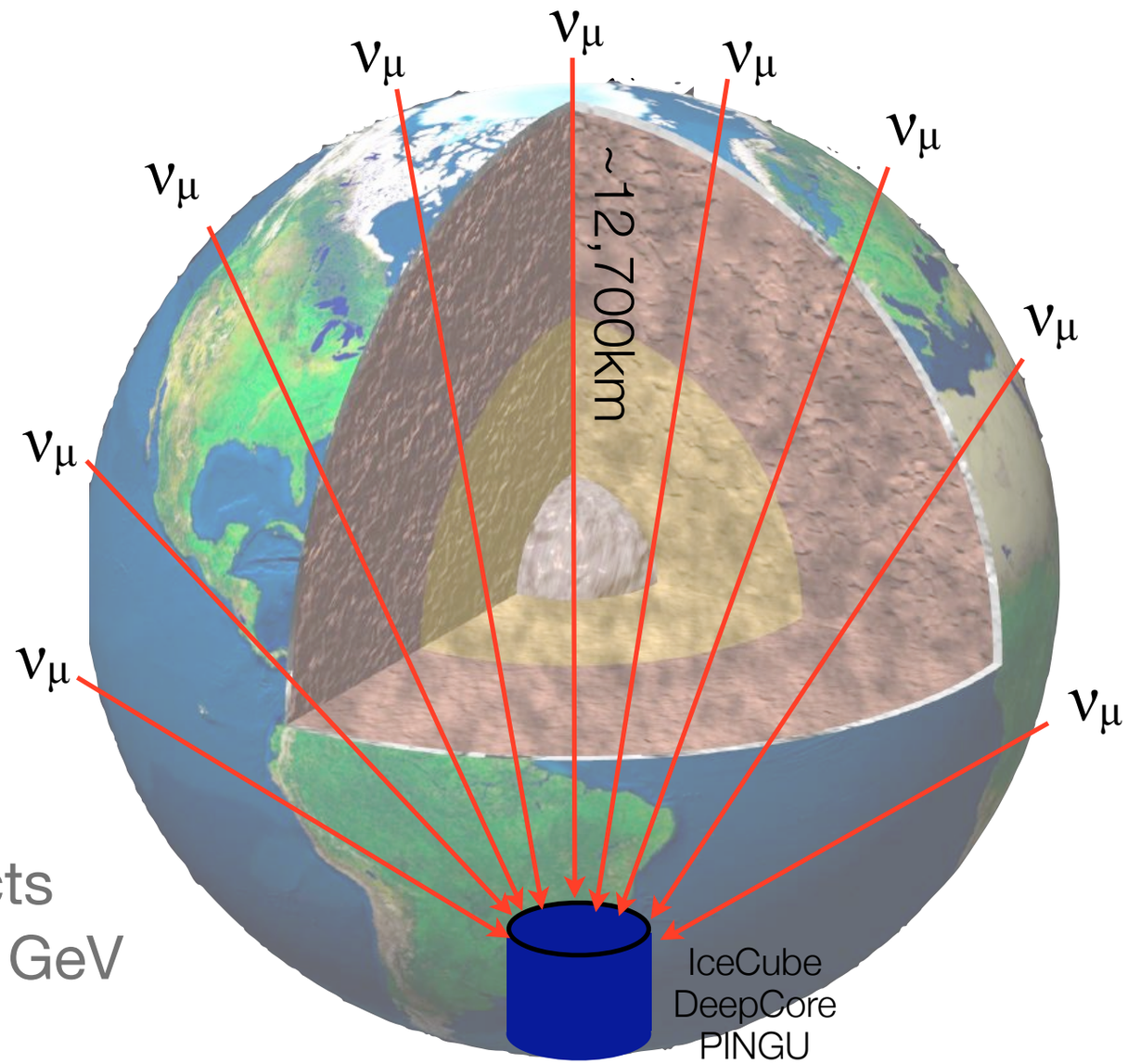
Tyce DeYoung
Department of Physics and Astronomy
Michigan State University



Workshop on the Intermediate Neutrino Program
Brookhaven National Laboratory
February 5, 2015

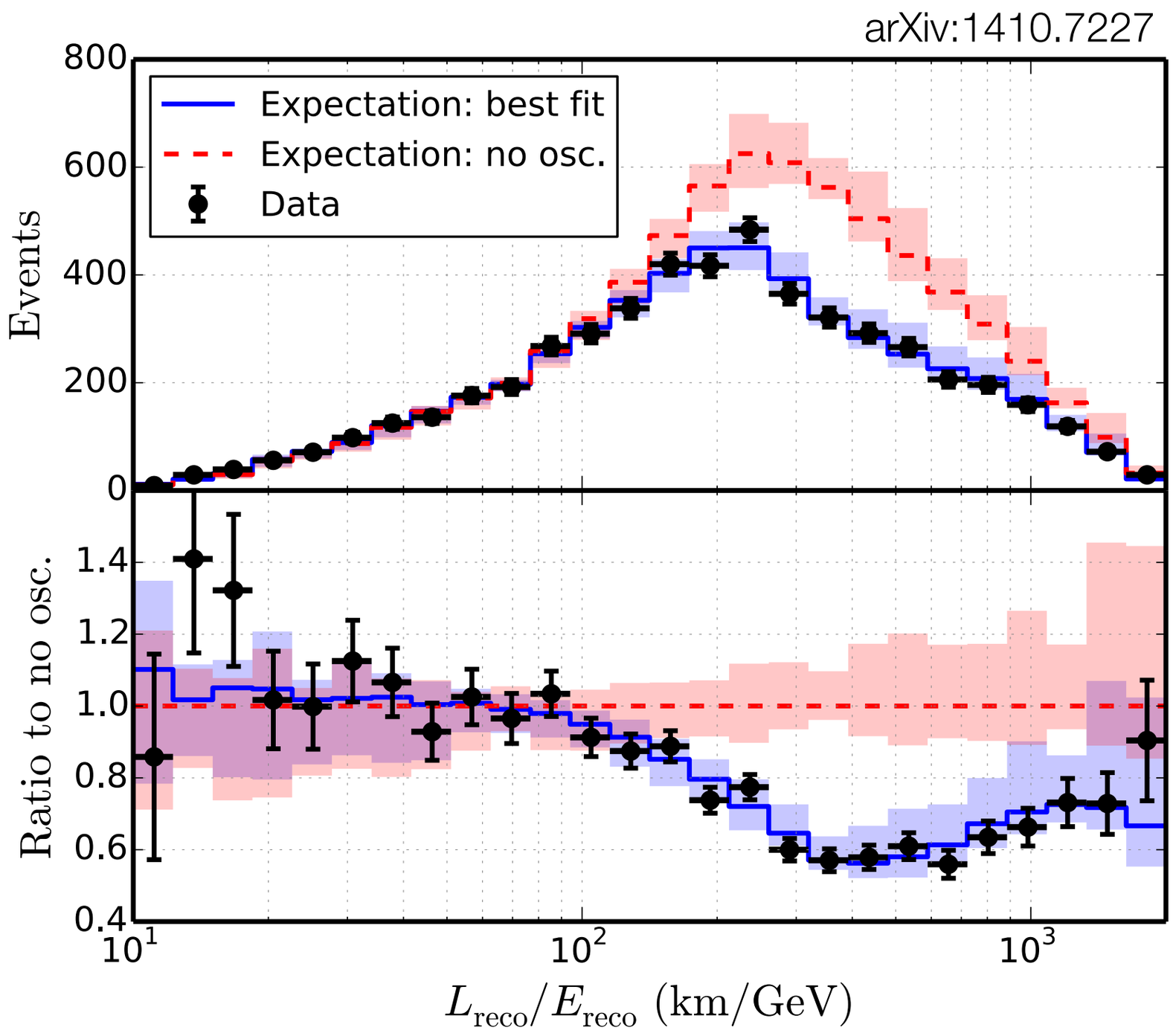
Oscillation Physics with Atmospheric Neutrinos

- Neutrinos available over a wide range of energies and baselines
  - Oscillations produce distinctive pattern in energy-angle space
  - Approach: control systematics using events in “side band” regions – trade statistics for constraints on systematics
- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects on ν or $\bar{\nu}$ (MSW etc.) below 10-20 GeV



Atmospheric Oscillations with IceCube

- Project data onto reconstructed (L/E_ν) for illustration
  - Actual analysis is performed in 2D to control systematics
- Shaded range shows allowed systematics with constraints from current data
- Second survival maximum just below DeepCore's energy threshold

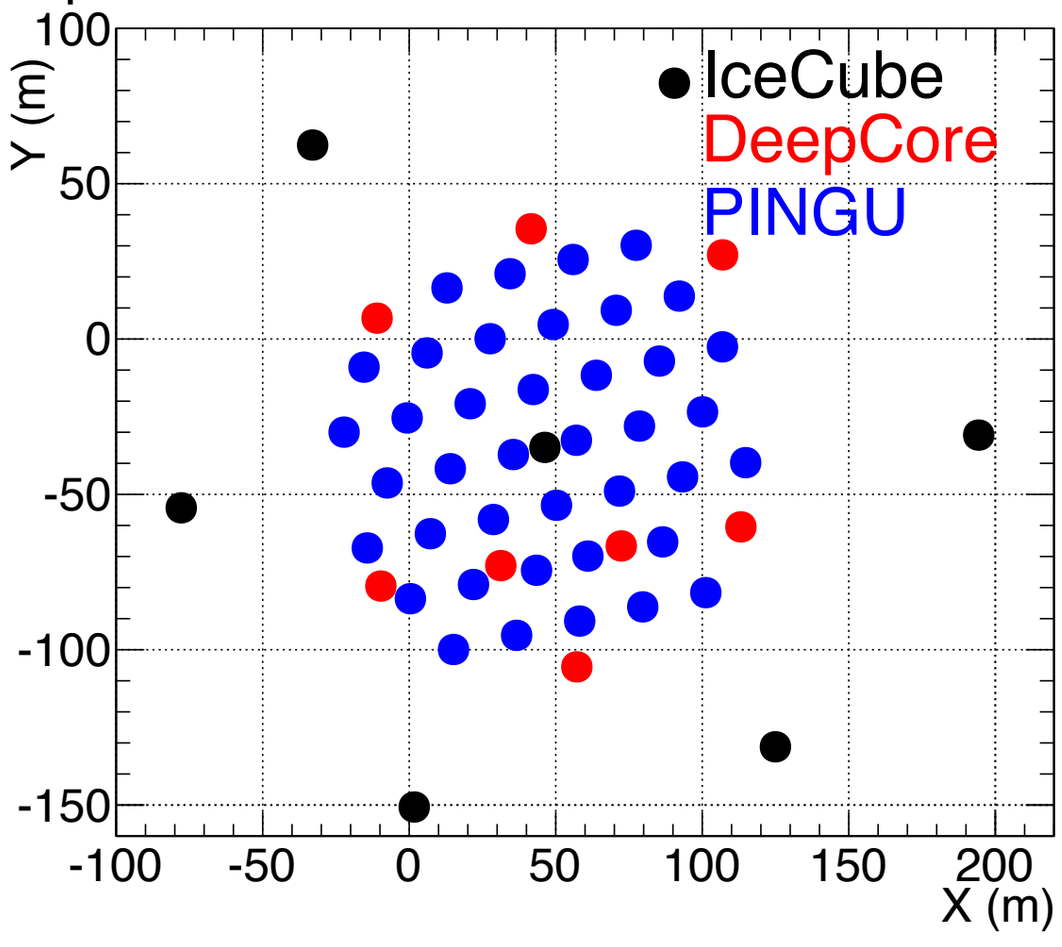


PINGU

PRECISION ICECUBE NEXT GENERATION UPGRADE

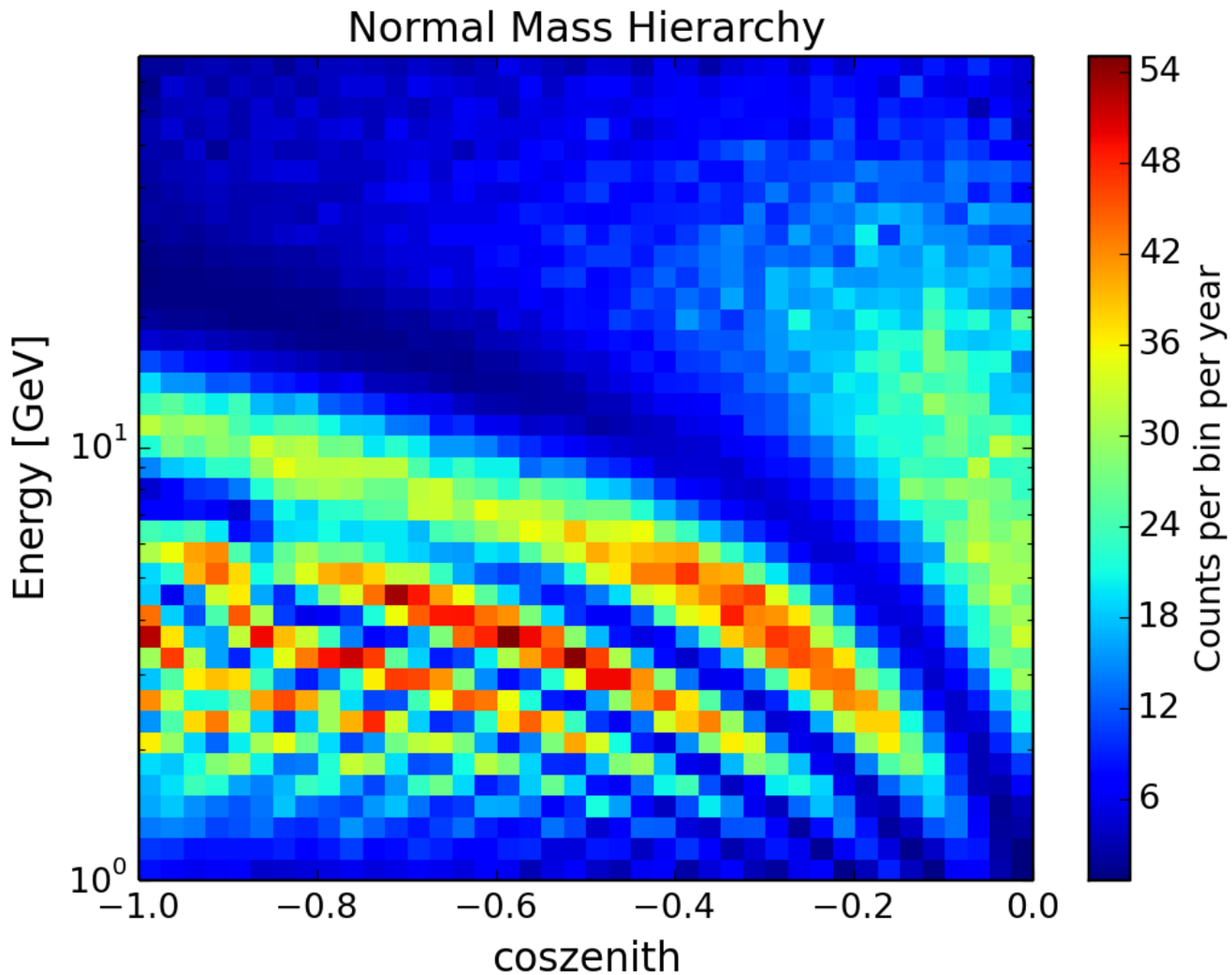
- Baseline detector consists of 40 additional strings of 60 Digital Optical Modules each, deployed inside the DeepCore volume
  - Geometry optimization underway – additional DOMs have relatively low incremental cost – final proposal likely 80-96 DOMs/string
  - 20-22 m string spacing (cf. 125 m for IceCube, 72 m for DeepCore)
    - ~25x higher photocathode density
    - Additional in situ calibration devices will better control detector systematics (not included in projected performance)
- Engineering issues and cost of deploying instrumentation are well understood from IceCube experience
  - Can install ≥20 strings per season once underway

Top view of the PINGU new candidate detector



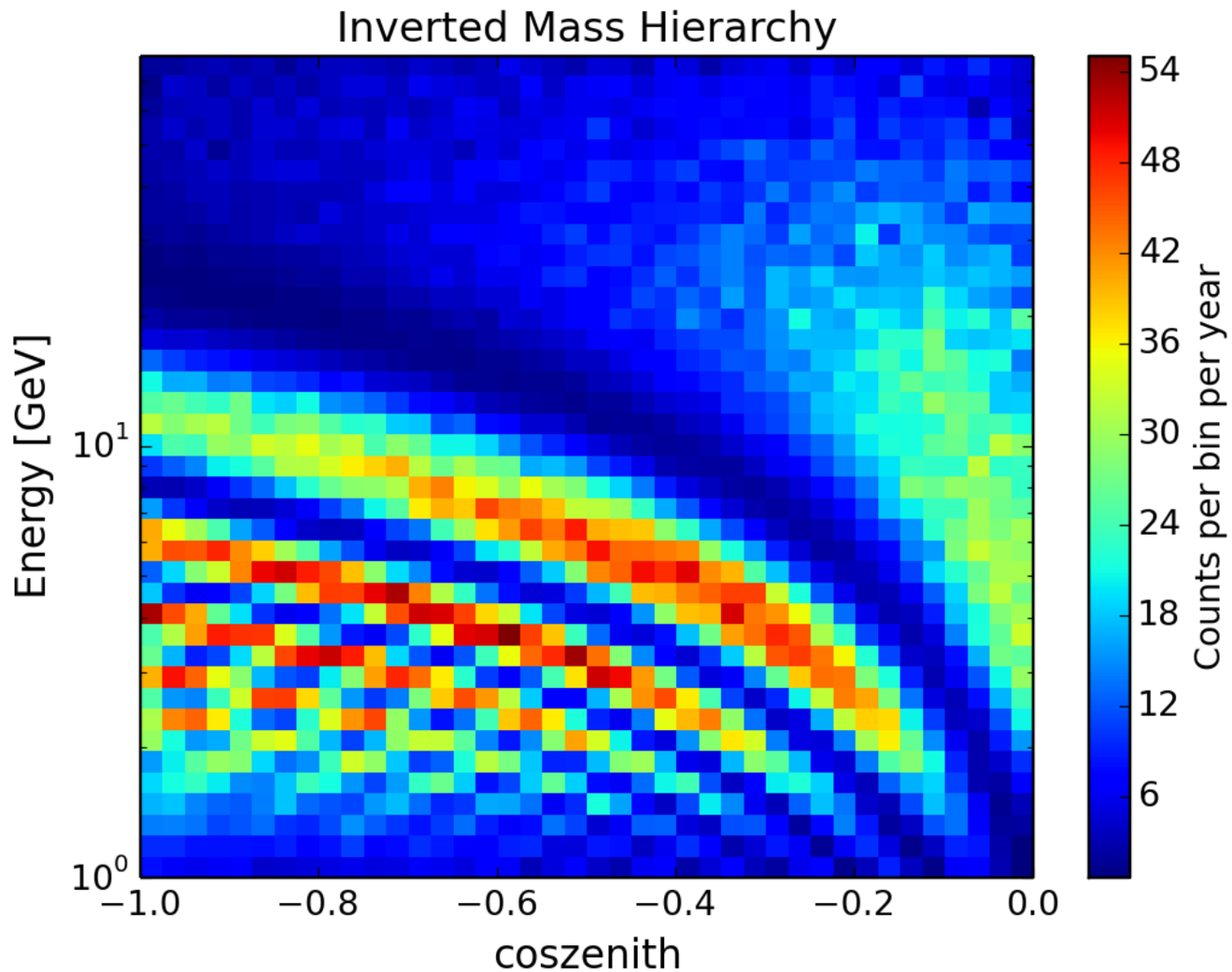
Signatures of the Neutrino Mass Hierarchy

- Matter effects alter oscillation probabilities for neutrinos or antineutrinos traversing the Earth
  - Maximum effects seen for specific energies and baselines (= zenith angles) due to the Earth's density profile
  - Neutrino oscillation probabilities affected if hierarchy is normal, antineutrinos if inverted
  - Rates of all flavors are affected
  - Note: effect of detector resolution not shown here
- Distinct signatures observable in both track (ν_μ CC) and cascade (ν_e and ν_τ CC, ν_x NC) channels
  - At higher energies, ν_μ CC events distinguishable by the presence of a muon track



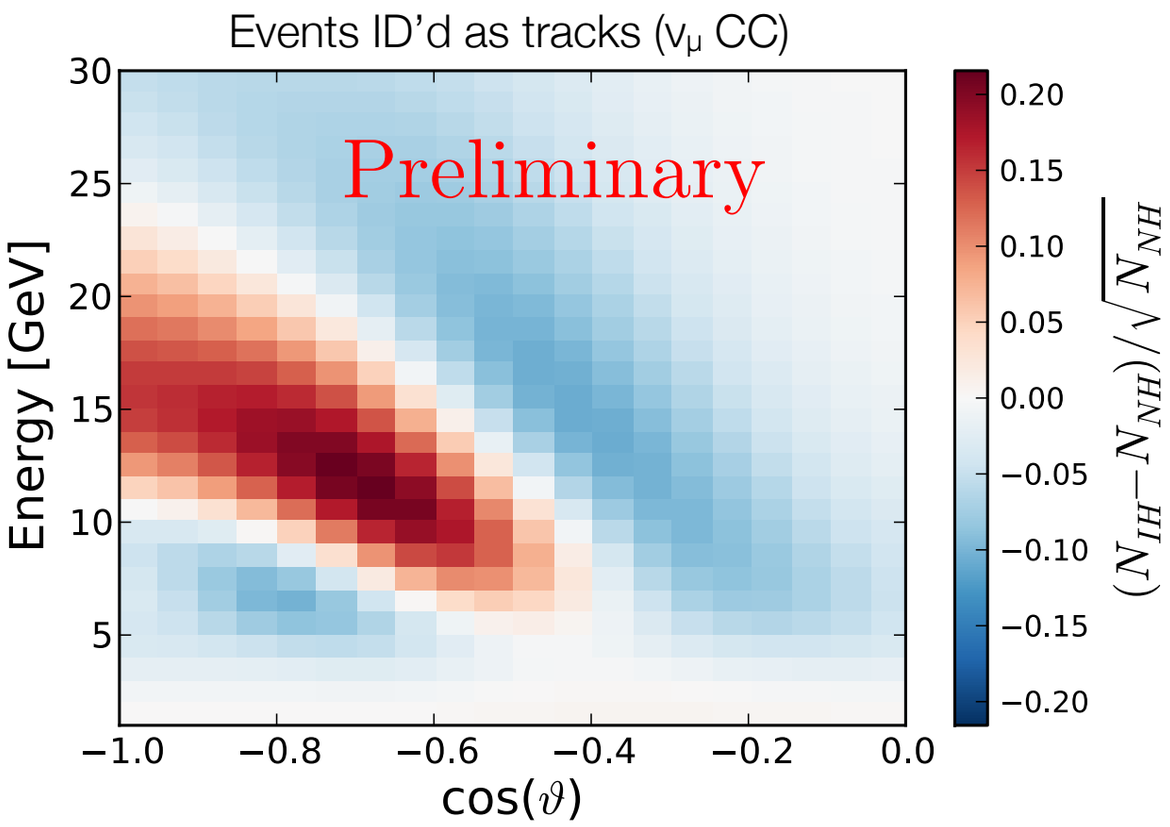
Signatures of the Neutrino Mass Hierarchy

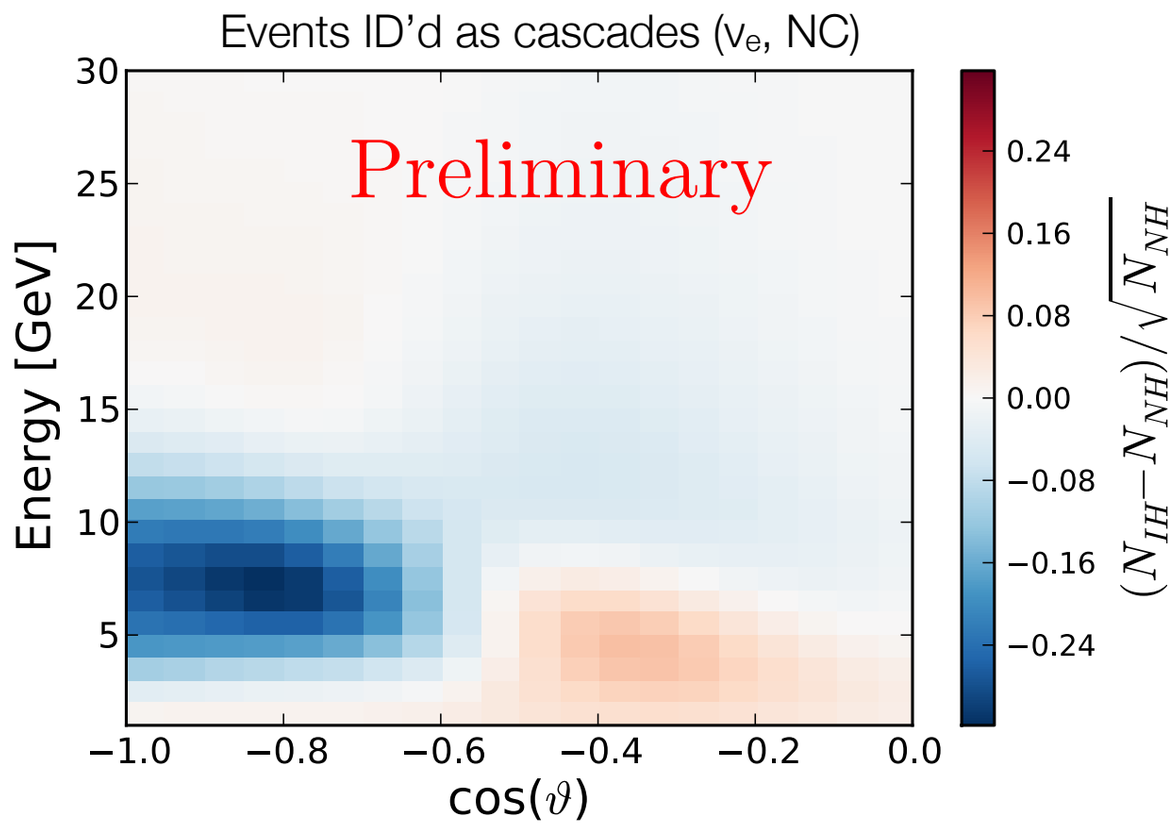
- Matter effects alter oscillation probabilities for neutrinos or antineutrinos traversing the Earth
  - Maximum effects seen for specific energies and baselines (= zenith angles) due to the Earth's density profile
  - Neutrino oscillation probabilities affected if hierarchy is normal, antineutrinos if inverted
    - Rates of all flavors are affected
    - Note: effect of detector resolution not shown here
- Distinct signatures observable in both track (ν_μ CC) and cascade (ν_e and ν_τ CC, ν_x NC) channels
  - At higher energies, ν_μ CC events distinguishable by the presence of a muon track



Hierarchy Signature: Statistical Significance

arXiv:1401.2046





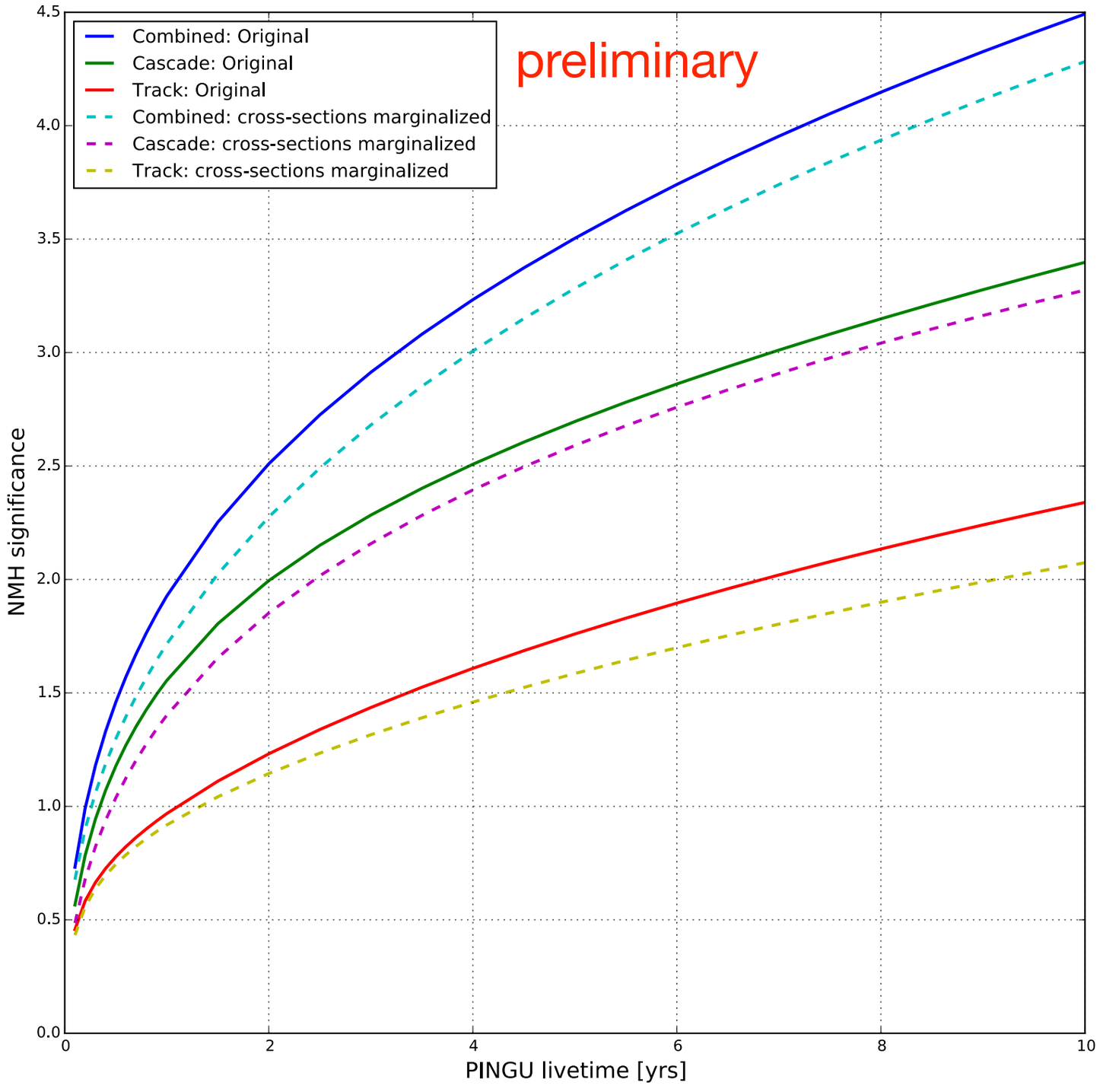
- With full detector response included, distinctive (and quite different) hierarchy-dependent signatures are still visible in both the track and cascade channels
  - Quantity shown is an illustration of statistical significance per bin (as per Akhmedov et al. arXiv:1205.7071)
  - Parametrized rates and detector resolutions and efficiencies used to eliminate statistical fluctuations

Analysis Improvements Underway

- Increased #DOMs/string to match baseline Gen2 High Energy design (marginal cost of DOMs is relatively small)
- Inclusion of additional detector-related effects on event reconstruction – appears minimal
  - Uncertainties in optical properties of South Pole ice (e.g. anisotropic scattering)
  - Injecting DOM-by-DOM calibration errors for sensitivity to Cherenkov photons, in addition to possible systematic errors in energy scale calibration (already included)
- Correcting Monte Carlo error in non-Poissonian noise levels in simulated PINGU DOMs
- Treatment of ν-N interaction uncertainties via GENIE instead of ad hoc scaling
- Detailed modeling of atmospheric flux uncertainties (per Barr et al. astro-ph/0611266) rather than simpler scaling of flux level and spectral index
- Incorporating full suite of systematic uncertainties into likelihood-based significance estimates from ensemble of pseudo-data sets (so far only checks with reduced sets)

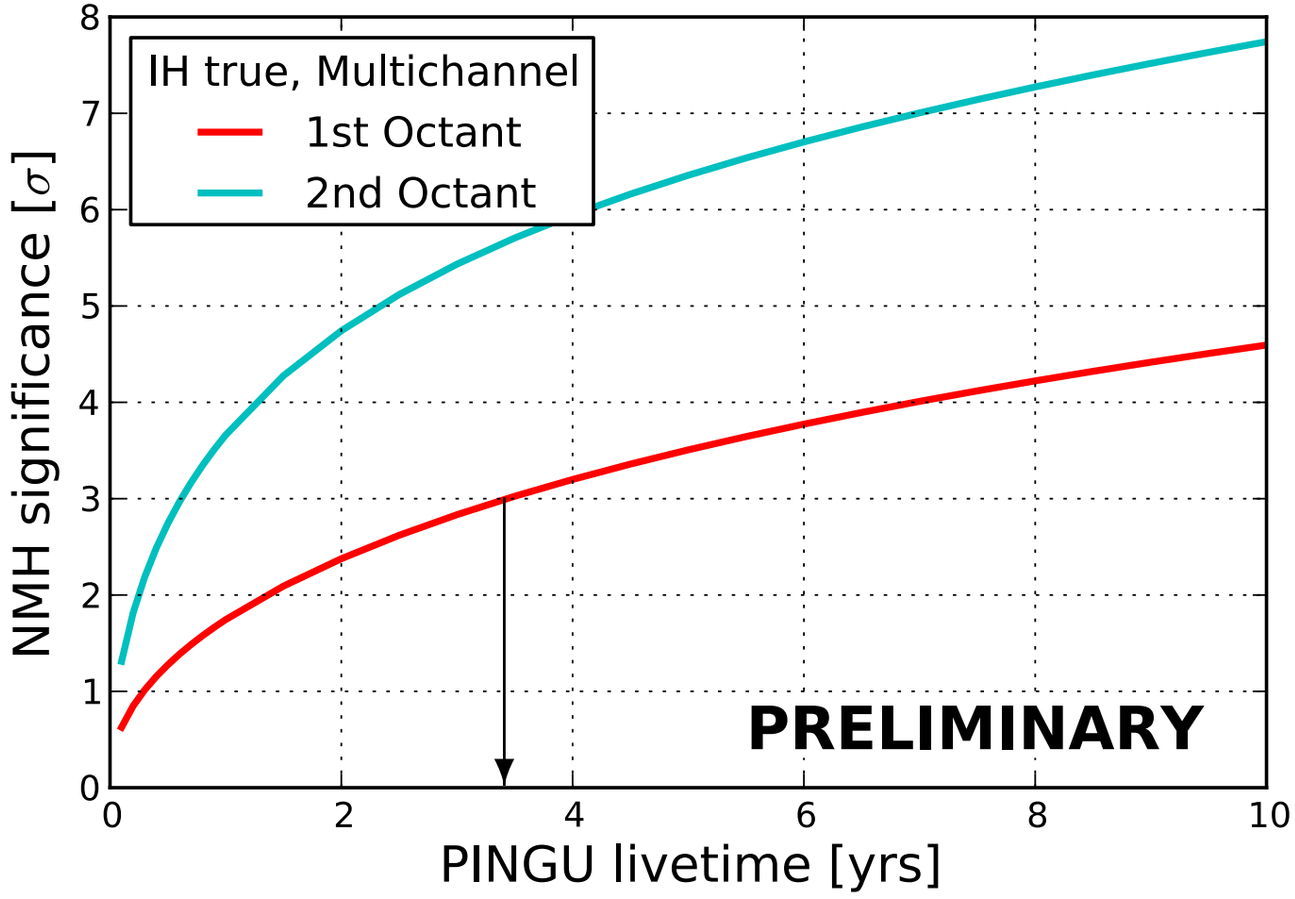
Neutrino Interaction Uncertainties

- Biggest effects so far: uncertainties in Bodek-Yang higher twist parameters, axial mass term for hadron resonance production
  - Ad hoc scalings still included, and covariance not accounted for – may be over-counting…
- Increases median time-to-3σ by about half a year



Other Oscillation Parameters

- PINGU not sensitive to δ_{CP} – complementarity with NOvA, T2K
- Sensitivity to the mass ordering strongly dependent on θ_{23} octant
  - Worst-case first octant solution assumed in performance studies
  - Implies considerable ability to measure octant (not yet evaluated explicitly)



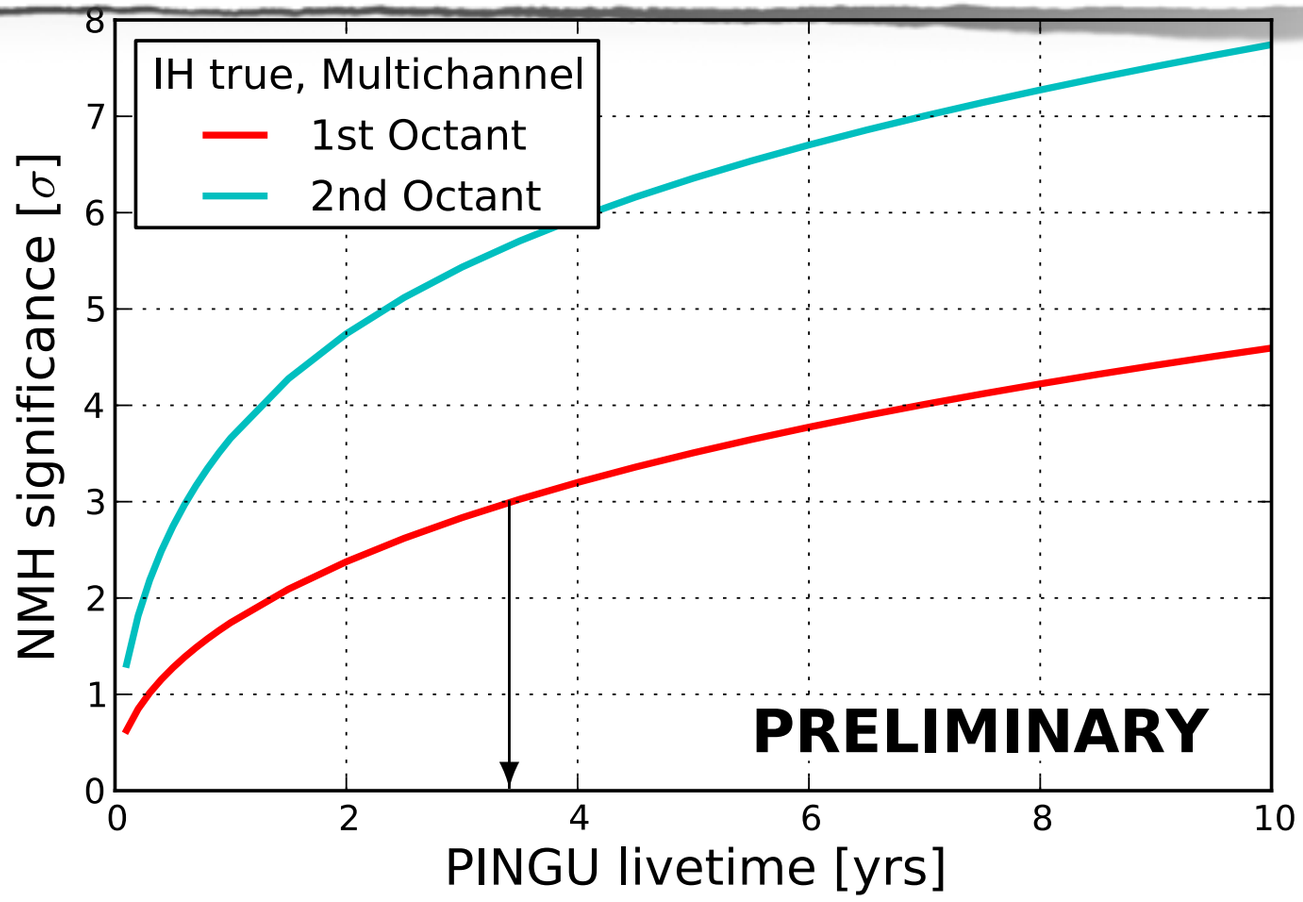
- Precision for θ_{23} and Δm^2_{atm} being evaluated, appears comparable to NOvA or T2K 2020 expectations

For the difference of the numbers of events for the two hierarchies (3.6) we obtain

$$D_\mu^{\rm IH} - D_\mu^{\rm NH} \approx \sigma^{\rm CC}\Phi_\mu^0\left\{\frac{1}{2}\sin^2 2\theta_{23}(1-\kappa_\mu)\left(\cos\phi_{32} - \sqrt{1-P_A}\cos\phi_X\right) + \right.$$
$$\left. + s_{23}^2\left[(1-\kappa_\mu)s_{23}^2 - \left(\frac{1}{r} - \frac{\kappa_\mu}{\bar{r}}\right)\right]P_A\right\}.$$

Akhmedov, Razzaque, and Smirnov arXiv:1205.7071

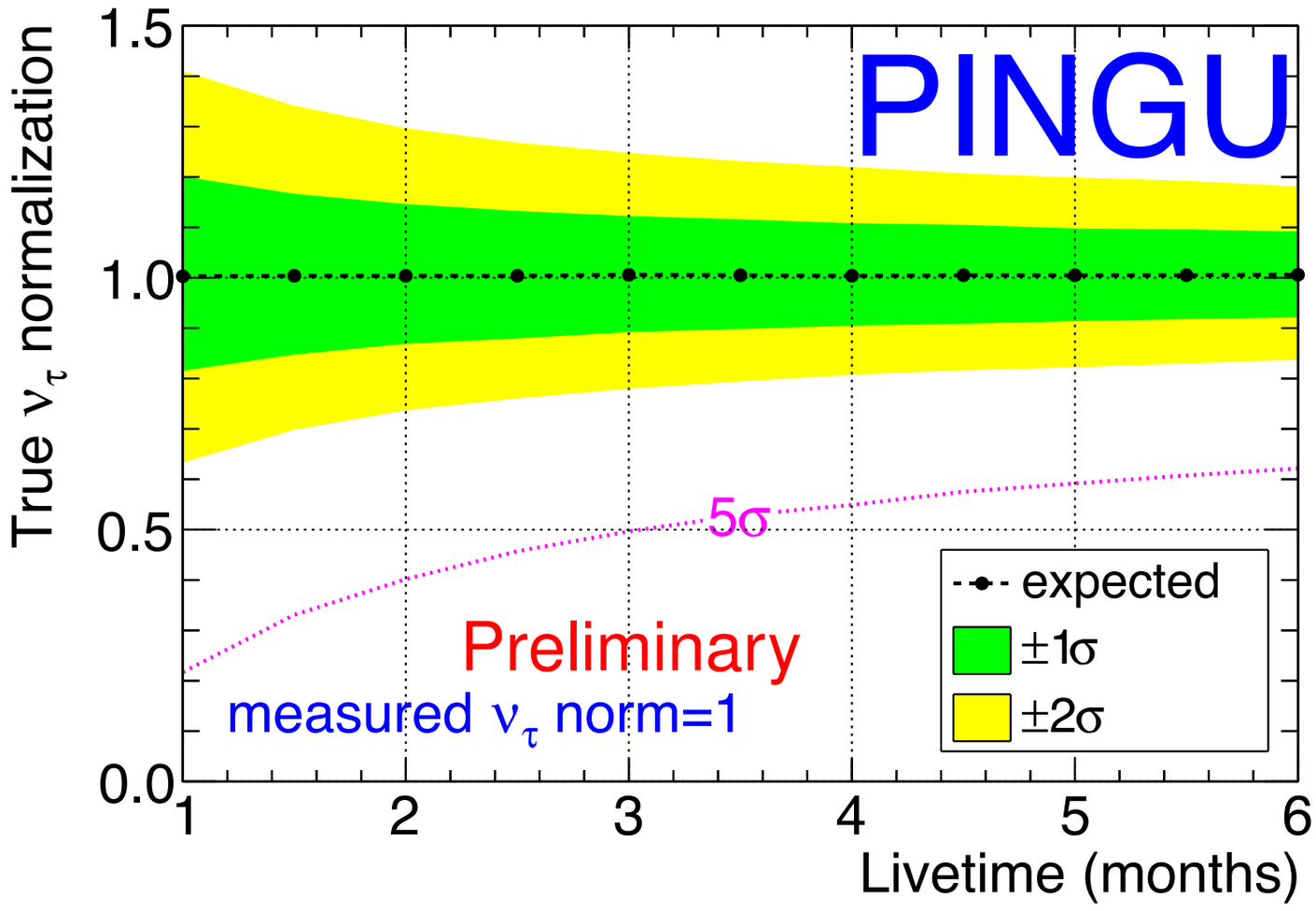
- Sensitivity to the mass ordering strongly dependent on θ_{23} octant
  - Worst-case first octant solution assumed in performance studies
  - Implies considerable ability to measure octant (not yet evaluated explicitly)



- Precision for θ_{23} and $\Delta m^2_{\rm atm}$ being evaluated, appears comparable to NOvA or T2K 2020 expectations

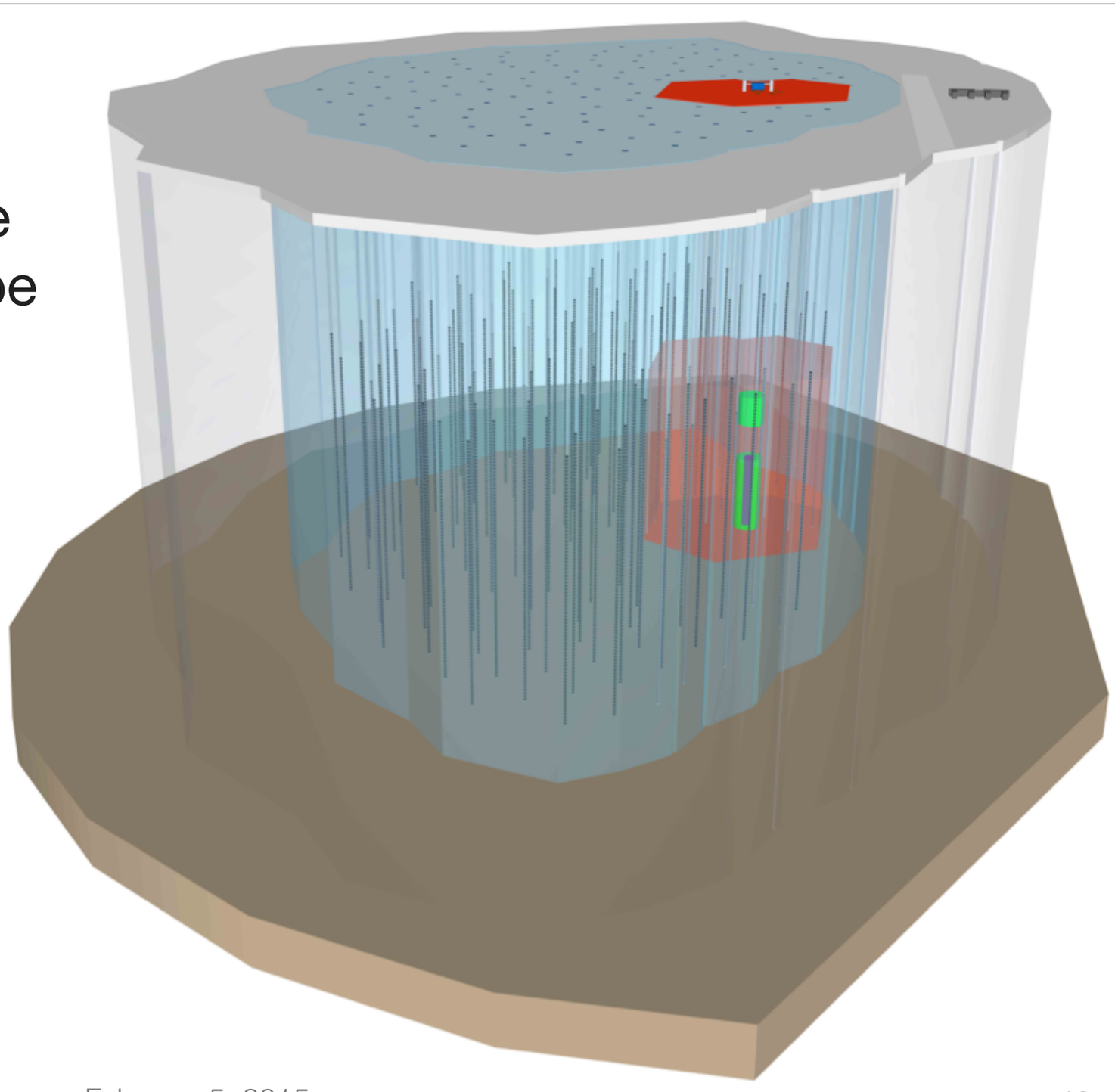
Tau Neutrino Appearance

- Energy range of PINGU allows uniquely high tau neutrino rates
  - Measure ν_τ appearance as characteristic distortion of cascade angular/energy distribution
- Interesting test of unitarity of 3x3 neutrino mixing
  - Direct probe of $U_{\tau 3}$
  - 10% precision on ν_τ appearance rate within a year



IceCube-Gen2

- Planning underway for a multipurpose facility leveraging the experience and investment in IceCube
  - White paper describing our vision of this detector at arXiv:1412.5106
- PINGU will be one component of IceCube-Gen2



Cost and Schedule

- Primary US funding source for IceCube-Gen2 would be NSF
  - MREFC-scale facility, total cost comparable to original IceCube
  - Many items common to PINGU and other elements (drill, engineering, etc.)
    - Marginal cost of PINGU within larger IceCube-Gen2 is $88M, with expected non-US contributions of $25M
- Gen2 conceptual design document and PINGU performance update this year
- In a favorable scenario, PINGU completion possible by January 2021 or 2022

Cost for PINGU Component	
Hardware	$48M
Logistics	$23M
Contingency	$16M
Expected non-US contributions	$25M
Total US Cost	$63M

(elements do not sum to total due to rounding)

Conclusions

- PINGU has a unique place in the world-wide neutrino program
  - Measurements at a range of higher energies/longer baselines, with high statistics
- Opportunity to discover new physics is greatly enhanced by PINGU's complementarity with other experiments
- PINGU will be a natural part of the IceCube-Gen2 Observatory
  - Closely based on IceCube technology – low technical and cost risk
  - PINGU will use the same hardware as high energy extensions of IceCube – common design gives flexibility to optimize based on progress of the field
- Focus today is on neutrino physics, but also interesting potential in searches for low mass dark matter and other exotica

Backup Slides

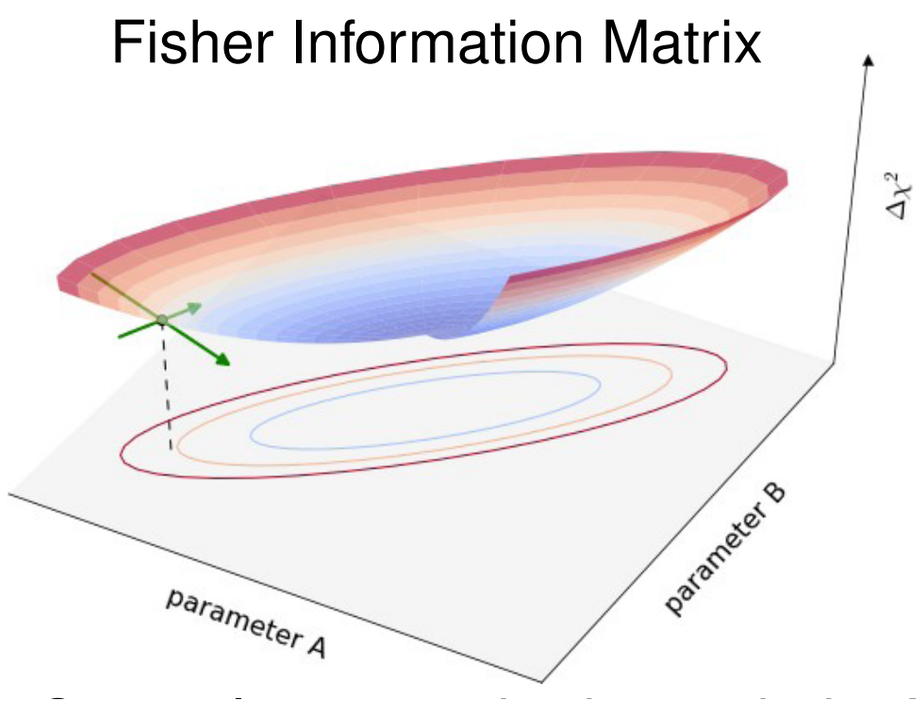
IceCube 2014 [NH]
T2K 2014 [NH]
MINOS w/atm [NH]
SK IV [NH]
90% CL contours
$-2\Delta\ln L$
$|\Delta m^2_{32}|$ $(10^{-3}\,\mathrm{eV}^2)$
$\sin^2(\theta_{23})$
$-2\Delta\ln L$
arXiv:1410:7227

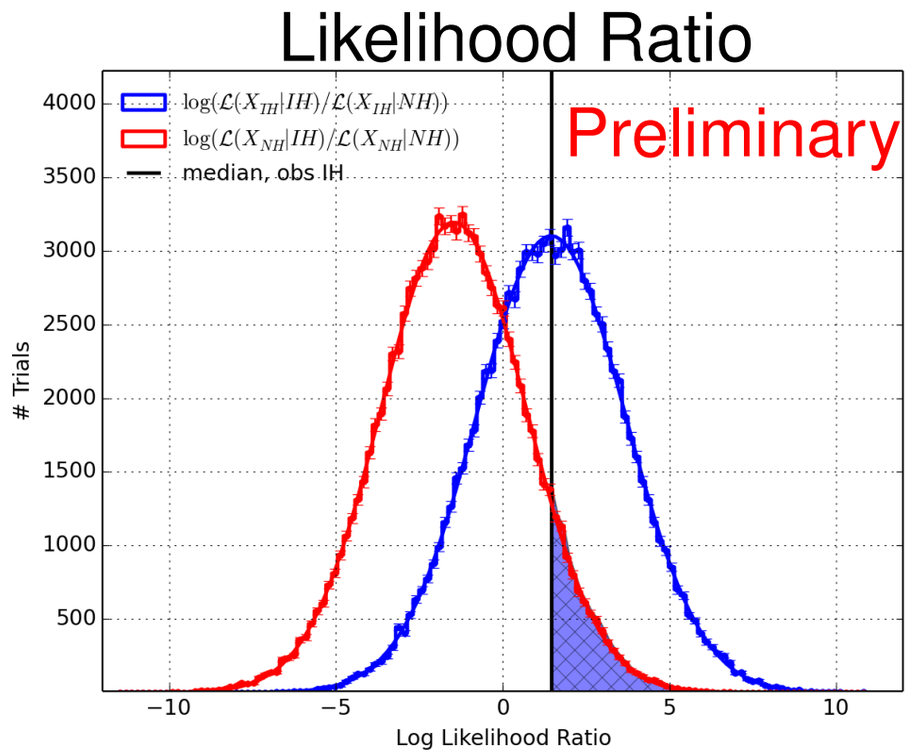
Estimating Sensitivity to the Mass Hierarchy

- Fisher Information Matrix method uses parametrized detector response based on full simulation, uses gradients in likelihood space to determine width of parabolic minimum

- Full Monte Carlo method uses likelihood ratio analysis of pseudo-data sets: slower, includes fewer systematics but does not pre-suppose distributions are Gaussian

- For common set of systematics and high statistics, the methods agree



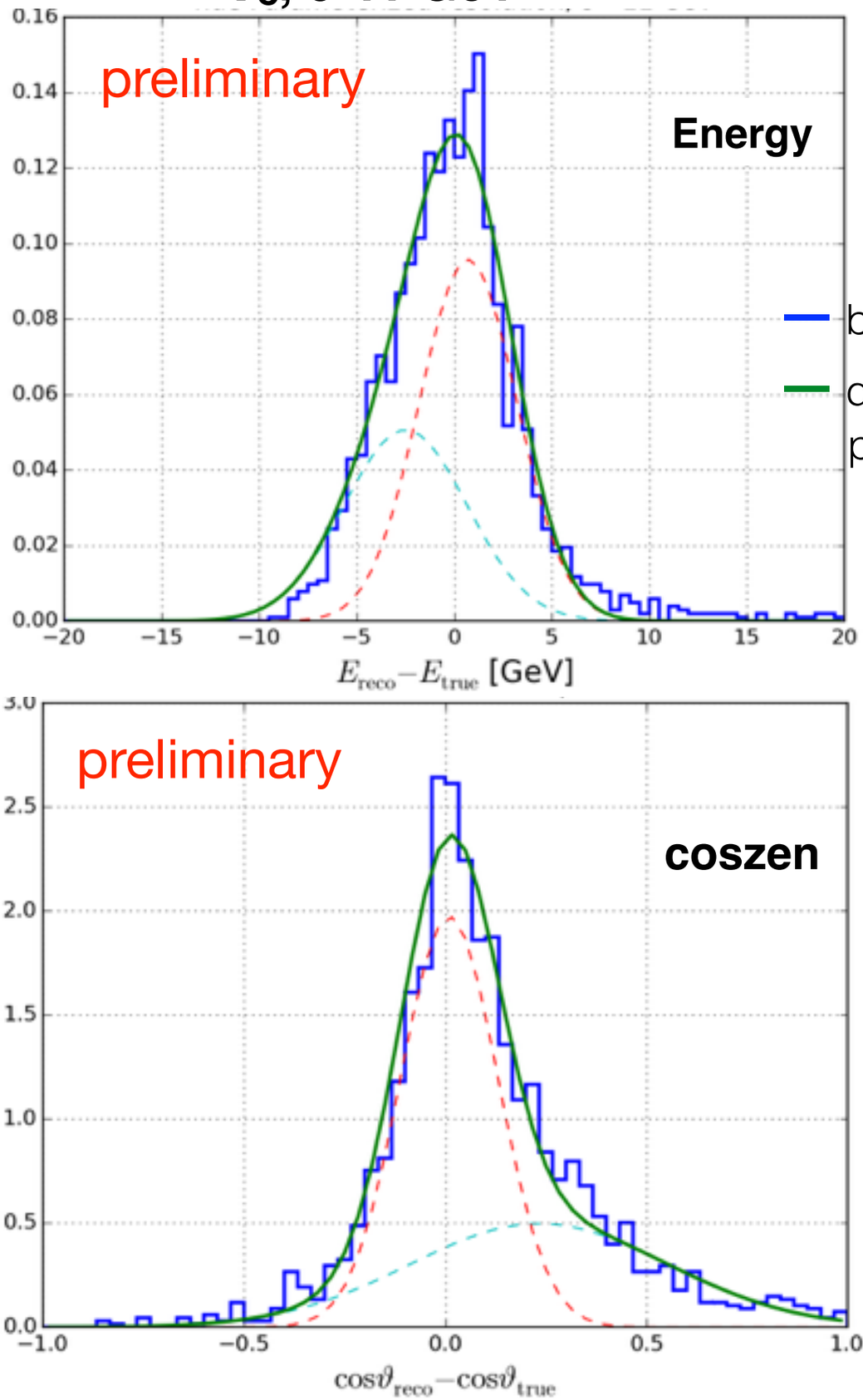


Relative Impact of Systematics

preliminary

Parameter	Total (%)	Cascades (%)	Tracks (%)
hierarchy	100.0	100.0	100.0
Δm_{31}	13.9	10.4	32.6
$\overline{\nu}$ xsec scale	12.2	4.2	0.1
higher-twist BY	10.3	6.9	12.3
MaCCRES	8.1	2.7	5.2
θ_{13}	5.4	2.0	5.2
Cν-BY	5.1	0.8	10.2
θ_{23}	5.0	10.5	16.4
energy scale	1.0	2.0	3.8
ν xsec scale	0.8	4.5	0.2
MaCCQE	0.6	3.2	1.7
effective area scale	0.1	1.6	1.0

Resolutions



binned reco - true

double gauss parameterization